SUB-MICRON ACCURACY EDGE DETECTOR

FIELD OF THE INVENTION

This invention relates generally to the field of assembly and test of electronic or optical components, such as integrated optical devices, and in particular to edge detection.

BACKGROUND OF THE INVENTION

The assembly and test of devices, such as integrated optical devices, require accurate alignment of components. For example, the assembly process for coupling optical fibers to optical chip components currently requires mechanical positioning to within 1 micron or less. The mechanical repeatability of chip placement equipment or manual loading of an optical chip into a test and assembly station, however, is much greater than 1 micron. Thus the position of the mating edges of a chip with respect to the mating fibers is known to an accuracy of no better than several microns. Consequently, additional steps must be taken to achieve sufficient accuracy in the relative positions of the components.

One approach is the use of a microscope together with manual positioning of the components. This approach requires trained and skilled operators. This is expensive and is subject to human error.

Another approach is the use of video microscopes in combination with image processing software and computer control of the positioning device. This type of equipment is expensive and relatively slow, and measurement accuracy is limited to a few microns.

The equipment used in these approaches tends to obstruct other processing equipment required to complete the assembly and test processes.

A further approach is the use of a light source and a light sensor to detect the edge of an object. The amount of light reaching the detector is reduced as the object obstructs the light path between the source and sensor. The accuracy of this approach is limited by the size of the detector and the accuracy to which the intensity of the light can be measured. Variations in the transfer efficiencies from the input current to the light source to the output current of the sensor introduce variability into the system, which limit the accuracy of this type of device. U.S. Patent No. 5,187,375 to Masten describes an edge detection device with two detectors with the aim of mitigating this problem. However, in systems of this type, the accuracy is limited firstly because the sensor is responsive to ambient light and light from the source and secondly because the size of the detector is large compared to the sub-micron accuracy required. In the Masten detector, the sensor is much larger than the source and has a length of 100 mils (0.1 inches).

A still further approach is laser interferometry, in which the phase difference between a transmitted and a reflected beam of monochromatic light is used to determine a position. The approach requires complex equipment and is very expensive.

Accordingly, there is an unmet need in the art for an edge detector capable of determining the edge of an object to within a fraction of a micron.

Further, there is an unmet need for a non-contact positioning system that is capable of operating automatically and in real-time.

Still further, there is an unmet need for a non-contact positioning system that achieves sub-micron accuracy at a low cost.

BRIEF SUMMARY OF THE INVENTION

The invention relates generally to a method and apparatus for edge detection with sub-micron accuracy. The edge detection apparatus comprises two single mode optical fibers with an optical path between them. One fiber is coupled to a laser light source, and creates a light beam. The other fiber is coupled to an optical power detector. The optical power reaching the optical power detector is determined by how much of the light beam is obscured by an object. Thus the position of an edge of the object may be determined from the optical power measured by the detector.

An object may be positioned automatically according to the optical power measured by the detector.

BRIEF DESCRIPTION OF THE DRAWINGS

The novel features believed characteristic of the invention are set forth in the claims. The invention itself, however, as well as the preferred mode of use, and further objects and advantages thereof, will best be understood by reference to the following detailed description of an illustrative embodiment when read in conjunction with the accompanying drawing(s), wherein:

Figure 1 is a diagrammatic representation of an edge detector in accordance with an embodiment of the invention.

Figure 2 Is a graphical representation of an exemplary relationship between the position of an object and the output of an edge detector in accordance with the invention.

Figure 3 is a diagrammatic representation of an automatic positioning system incorporating an edge detector in accordance with one embodiment of the invention.

Figure 4 is a diagrammatic representation of a fiber retainer of an edge detector of the invention.

Figure 5 is a flow chart depicting the method of positioning the edge of an object in accordance with the invention.

Figure 6 is a representation of the preferred embodiment of the edge detector of the invention.

Figure 7 is a representation of a system incorporating an edge detector in accordance with the invention.

Figure 8 is a representation of a system incorporating an edge detector in accordance with a further embodiment the invention.

DESCRIPTION OF THE INVENTION

While this invention is susceptible of embodiment in many different forms, there is shown in the drawings and will herein be described in detail one or more specific embodiments, with the understanding that the present disclosure is to be considered as exemplary of the principles of the invention

and not intended to limit the invention to the specific embodiments shown and described. In the description below, like reference numerals are used to describe the same, similar or corresponding parts in the several Views of the drawings.

According to an apparatus of the present invention, an edge detector is provided that may be utilized for the detection of the edge of an object, such as an optical chip. Referring to the edge detector 100 shown in **Figure 1**, a first optical fiber 102, with a receiving end 104 and a transmitting end 106, is optically coupled to a laser light source 108, such as an L-band or C-band laser, at the receiving end 104 and creates a light beam at the transmitting end 106. A second optical fiber 110, with a receiving end 112 and a transmitting end 114, is optically coupled to an optical power detector 116 at the transmitting end 114. The optical power detector may be a junction photodiode, for example. The two optical fibers, 102 and 110, are held in place by a retainer 118, and positioned so that there is an optical path from the transmitting end 106 of the first fiber to the receiving end 112 of the second fiber. The light beam transmitted by the first optical fiber 102 is received by the second optical fiber 110 and transmitted to the optical power detector 116. In the preferred embodiment, the transmitting end of the first fiber 102 and the receiving end of the second fiber 110 are held co-axially in opposition, so that light passes directly from the first fiber to the second fiber. Only the ends of the fibers need be aligned, the remainder of the fibers may have any orientation. In a further embodiment, the optical path is indirect and may include one or more mirrors which reflect the light beam. While this may impair performance slightly, it may provide other benefits in some

applications. In the preferred embodiment, the optical power detector converts the optical power into an electrical signal that may be coupled to a display or to a controller of a positioning system, as will be discussed later.

The optical power detector may measure any quantity related to the amount of light reaching the detector. For example, the amplitude, root mean square amplitude or any function thereof may be used.

In the preferred embodiment, the fibers are single mode optical fibers. The transmitting end of the first fiber and the receiving end of the second fiber are positioned co-axially with a gap between them. Relative motion of the fibers may cause variation in the amount of light transmitted from the first fiber to the second fiber. In the preferred embodiment, the fibers are held in a retainer 118 so as to prevent relative motion of the fibers.

When the optical path between the two fibers is not obstructed, the optical power at the detector is at a maximum. The maximum power at the detector is denoted by P_{max}. When an object partially obstructs the optical path, part of the light beam is prevented from reaching the detector, and the optical power at the detector is attenuated. The power at the detector is

$$P(d) = P_{\max} F(d, \gamma),$$

where d is the depth the object has penetrated the beam and $F(d)$ is a function dependent upon the distribution of light across the cross-section of the light beam and the optical properties of the object. The object may be partially translucent, so that optical power is not zero when the whole of the beam in interrupted by the object. This is often the case when the object is an optical component.

The ratio of the power at the detector to the maximum power is denoted as

$$F(d) \equiv \frac{P(d)}{P_{\max}}.$$

The function $F(d)$ takes the value 1 when the object is outside of the beam. In one embodiment, the function $P(d)$ is determined by calibration. In a further embodiment, the function $F(d)$ is determined by calibration. This function may vary less over time than the function $P(d)$, since it does not depend upon the strength of the laser source. In order to determine the function $F(d)$, the optical power $P(d)$ is be measured as a function of distance d and the function F is calculated from the ratio of powers as $F(d) = \frac{P(d)}{P_{\max}}$.

The position of the object may be obtained as

$$d = F^{-1}\left[\frac{P(d)}{P_{\max}}\right],$$

where the inverse function F^{-1} is evaluated analytically or by use of a look up table.

A plot of the power at the detector relative to the maximum power, $F(d) \equiv \frac{P(d)}{P_{\max}}$, measured in accordance with the invention, is shown in **Figure 2**. The horizontal axis in **Figure 2** denotes the distance of the edge of the object from the center of the beam. In this example, the object is opaque. When the edge is at the center of the beam, half of the power of the beam is blocked, giving a relative power of 0.5. The shape of the curve, which describes the relationship between the power measured at the detector and

the position of the object, is dependent upon the cross-section of the beam and the properties of the optical fibers. For a particular system, this relationship may be obtained by calibration.

An important property of the ratio of powers, denoted by the function *F,* is independent of the overall power or intensity of the laser light source. The ratio depends only on the distribution of light across the cross-section of the light beam and the optical properties of the object. These properties are generally not subject to change due to temperature variations, source strength, etc. The maximum power can be re-measured before an object enters the beam. This avoids the additional cost and complexity associated with prior edge detectors that required multiple sensors. In addition, laser light sources are generally very stable and monochromatic sources are less susceptible to interference from light reflected or refracted from nearby objects.

The sensitivity of the detector is quantified by how fast the ratio of powers changes with position. The ratio of power is a function of relative position d/D of the object, hence the rate of change of power with respect to distance is

$$\frac{\partial F(d)}{\partial d} = \frac{1}{D}\frac{\partial F(d)}{\partial (d/D)}.$$

The second term on the right hand side of the equation is a non-dimensional, geometric factor, so this shows that the sensitivity increases as the depth of the beam, D, decreases. Thus the use of a very narrow beam, as provided by the laser light source and single mode optical fibers of the present invention, results in a very sensitive edge detector. In general, the sensitivity is at a

maximum where the width of the beam (parallel to the edge) is greatest.

The sensitivity is further enhanced by the use of a laser light source because the light beam is monochromatic. Ambient light with wavelengths longer or short than the laser light wavelength can be filtered out by the detector. Further, light with wavelengths longer than the cut-off wavelength of the single mode fiber will be attenuated in the fiber.

In an automatic control system, the position of the object may be adjusted until the ratio of powers *R* is within a specified range. That is, the position is adjusted until the condition $\alpha < \frac{P(d)}{P_{\max}} < \beta$ is satisfied, where α and β are threshold levels which satisfy $0<\alpha<\beta<1$. The parameters α and β may be chosen to give a required accuracy relative to the width of the beam. Equivalently, the position of the object may be adjusted until the optical power *P* is within a specified range. For example, the position may be adjusted until the condition $\alpha P_{\max} < P < \beta P_{\max}$ is satisfied. The value of P_{max} may be predetermined or re-measured at regular intervals. In a still further embodiment, the position may be adjusted until the condition $P_{\min} + \alpha(P_{\max} - P_{\mathrm{mm}}) < P < P_{\min} + \beta(P_{\max} - P_{\mathrm{mm}})$ is satisfied. The value of P_{min} denotes the value of the optical power when the object completely obscures the beam. The value may be predetermined or re-measured at regular intervals. An advantage of this embodiment is that it is less sensitive to variations in opacity between different objects.

The object may be positioned using a positioning stage, controlled by a linear servo-motor for example. Such positioning stages capable of moving an object in increments of 50 nano-meters or less are commercially available.

For example, if it is desired that the object is to be positioned in the range $d_1<d<d_2$, the condition $P(d_2)<P(d)<P(d_1)$ must be satisfied, or, equivalently,

$$F(d_2)P_{\max} < P(d) < F(d_1)P_{\max}.$$

In this example the parameters are $\alpha=F(d_2)$ and $\beta=F(d_1)$. If the detector is used in conjunction with a positioning stage that is controlled in discrete steps of size δ, d_1 and d_2 may be chosen so that $d_1=d_0-\delta/2$ and $d_2=d_0+\delta/2$, where d_0 is the desired position.

In one embodiment, the positioning stage is controlled automatically by a controller. This is shown diagrammatically in **Figure 3**. The object is supported by a positioning stage 122, which allows the position of the object 120 to be adjusted relative to the position detector. A controller 124 receives the detector output signal 126 from optical power detector 116. The controller is preferably implemented in software running on a computer, but an analog controller may be used. In response to the detector output signal 126, the controller produces a control signal 128 that is passed to the positioning stage 122. One control strategy is to scan through a range of positions until the condition $P(d_2)<P(d)<P(d_1)$ is satisfied. Another control strategy is to change the position according to the difference between current optical power, $P(d_{current})$, and the optical power at the desired position, $P(d_0)$. This can be written as

$$d_{new} = d_{current} + G(P(d_{current}) - P(d_0))$$

where G is a linear or non-linear gain function, which may depend upon $P(d_{current})$ or $F(d_{current})$. For example, the gain function might be $G(x) = -\mu F^{-1}\left(\frac{x}{P_{\max}}\right)$, where μ is a parameter.

In a further embodiment, the detector may be moved to determine the position of an edge of a stationary object.

The optical fibers may be held by a fiber retainer. In the preferred embodiment, the fiber retainer comprises a retaining block with a beveled edge and a frame as shown in **Figure 4.** The optical fibers 102 and 110 are held in channels formed between the beveled edge of retaining blocks 402 and 404 and frame 406. The retaining blocks are preferably composed of a material that is compliant relative to the fiber so as to avoid damage to the fiber. A polycarbonate material, such as Delrin plastic, may be used. The frame 406 holds both optical fibers. A single retaining block may be used, or, as in **Figure 4**, one retaining block may be used for each optical fiber. The frame 406 holds the fibers coaxially in opposition to create a detection gap 408 for receiving an object. The frame 406 may also function as a guide for the optical fibers. The retaining blocks are shown as being rectangular in **Figure 4**. Other shapes may be used for the retaining blocks. For example, curved blocks may be used to change the orientation of the fibers so that the fibers emerge from the frame parallel to each other.

Other fiber retainers will be apparent to those skilled in the art. These include clamps of various kinds. The fibers may be embedded in the fiber

retainer or banded to it.

A flow chart depicting the method of positioning the edge of an object is shown in **Figure 5**. Starting at block 502, laser light is generated at block 504 from a laser light source. At block 506 the laser light is passed through a first optical fiber, coupled at one end to the laser light source. This forms a beam of light at the other end of the first optical fiber. The beam is received by the end of a second optical fiber at block 508 and is passed to an optical power detector at block 510. At decision block 512, a check is made to determine if the optical power is within a predetermined range. If it is within the range, as depicted by the negative branch from decision block 512, the predetermined amount of light is reaching the detector, which implies that a correct fraction of the beam is being block by an object within the beam, which in turn implies that the edge of the object is at the desired position relative to the detector. If the optical power is within the predetermined range, as depicted by the positive branch from decision block 512, the relative position of the object and the detector is adjusted. This may be achieved by moving the detector or by moving the object.

A representation of the preferred embodiment of the edge detector of the present invention is shown in **Figures 6(A)-6(C)**. **Figure 6(A)** is a side view of the edge detector 600. The edge detector 600 comprises an optical fiber 602 and output optical fiber 604 that are held between the frame 606 and retaining blocks 608. In this embodiment the face of the retaining blocks with a beveled edge are curved so as to bend the fibers through a 90° angle. The retaining blocks are secured to the frame 606 with screws 909 and 611 or other suitable securing means. The frame 606 functions as a guide for the

optical fibers. The optical fibers are further secured by a clamp 612 that is secured to the frame 606 by a screw 613 passing through a slot in the clamp. The clamp further restricts motion of the fibers with respect to the frame by holding the fiber between the face of the clamp and the frame. The light passes from the transmitting end of the input optical fiber 602 to the receiving end of the output optical fiber 604 across the detection gap 614. The laser light source and the optical power detector are not shown in this figure and may be at a remote location. **Figure 6(B)** shows the cross-section labeled as "A" in **Figure 6(A)**. The input optical fiber 602 is held in a channel formed between two faces of the frame 606 and the beveled edge of the retaining block 608. The retaining block 608 is secured to the frame 606 by screw 609. Figure 6(C) illustrates an isometric view of edge detector 600.

A system incorporating the edge detector is shown in **Figure 7**. An object 702 with an edge to be detected is placed in holder 704, which is in turn mounted on object positioning stage 706. The position of the holder 704 along the length of the object positioning stage 706 may be adjusted by a linear servo-motor or other suitable adjustment means. The edge detection device 708 is mounted on positioning platform 710, which is in turn mounted on detector positioning stage 712. The position of the holder 710 relative to the detector positioning stage may be varied by a linear servo-motor in a direction perpendicular to the object positioning stage 706. An edge detector calibration fiducial 714 is attached to the holder 704 at a known location and is used in the calibration of the edge detector.

In a further embodiment, the first and second fibers comprise a single fiber. Referring to **Figure 8**, an object 120 is supported by a positioning

stage 122, which allows the position of the object 120 to be adjusted relative to the position detector. A controller 124 receives the detector output signal 126 from optical power detector 116. The controller is preferably implemented in software running on a computer, but an analog controller may be used. In response to the detector output signal 126, the controller produces a control signal 128 that is passed to the positioning stage 122. A laser light source 108 is optically coupled via a first optical fiber 102 to a first port of a three port circulator. Light is transmitted though the three port circulator to a single fiber 804 coupled to the second port of the three port coupler. The light is transmitted to the end of the fiber 804 and creates a light beam. The optical fiber 804 held in place by a retainer 118, and positioned so that there is an optical path from the end 806 of the fiber to a mirror 802 and back to the end 806 of the fiber 804. The light beam received by the fiber is transmitted back to the second port of the three port circulator where it is guided to the third port of the circulator. An optical power meter 116 is optically coupled via a second optical fiber 110, to a third port of the three port circulator and receives the light reflected back from the mirror. When the object partially interrupts the light beam, the optical power reaching the optical power meter 116 is reduced. The position of the object may be adjusted by controller 124 in response to the output 126 from the optical power meter, so that the object is in a desired position relative to the fiber retainer 118.

It will be apparent to those of ordinary skill in the art that other optical devices, such as 3dB coupler, may be substituted for the three port circulator described above.

In a still further embodiment, the fiber retainer is attached to a positioning stage which, in turn, may be controlled by the controller 124, and the position of the fiber retainer is moved relative to the object.

While the invention has been particularly shown and described with reference to a preferred embodiment, it will be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention.

What is claimed is: